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Rishøj, Lars Søgaard; Chen, Y. ; Steinvurzel, P.; Rottwitt, Karsten; Ramachandran, Siddharth

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# High-energy fiber lasers at non-traditional colours, via intermodal nonlinearities

L. Rishøj<sup>\*,#</sup>, Y. Chen<sup>#</sup>, P. Steinvurzel<sup>#</sup>, K. Rottwitt<sup>\*</sup>, and S. Ramachandran<sup>#</sup>

<sup>#</sup>Boston University, Dept. of Electrical and Computer Engineering, 8 Saint Mary's St., Boston, MA 02215, USA

<sup>\*</sup>Technical University of Denmark, Ørstedes plads 343, 2800 Kgs. Lyngby, Denmark

rishoj@bu.edu, sidr@bu.edu

**Abstract:** We propose exploiting intermodal four-wave mixing for energy-scalable tuneable fiber lasers, hitherto restricted to low powers, constrained by dispersion-tailoring limitations in PCFs. Conversion over an octave, at mJ-energy-levels, appears feasible.

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While fiber lasers have made tremendous progress in power scaling in the 1 and 2- $\mu\text{m}$  wavelengths ranges, power scaling in other technologically attractive spectral ranges, such as blue-green, eye-safe wavelengths, or the mid-IR, has been limited because suitable dopants are not readily available. Wavelength conversion via four-wave mixing (FWM) in fibers is an attractive means of accessing these spectral ranges [1], and dispersion design with PCFs has enabled this [2]. Unfortunately, the requirement that the zero-dispersion-wavelength (ZDW) of the fiber be in the vicinity of the pump laser, combined with the fact that PCF designs fundamentally require reducing mode area ( $A_{\text{eff}}$ ) with pump wavelength, implies that this concept is not power/energy scalable.

Here, we propose a new path for exploiting fiber nonlinearities without being constrained by mode area and thus power-level limitations. This is based on the realization that ZDW in higher order modes (HOM) of fibers scales with mode order in analogy to ZDW scaling with mode area in photonic crystal fibers (PCFs) [3]. Moreover, since FWM requires that phase matching be achieved between the four interacting waves, and the ZDW requirement is only a result of applying this constraint in monomode fibers [1], it follows that the use of multiple modes to achieve this nonlinear interaction relaxes the ZDW constraint, opening up the design space of fibers even further [4, 5]. This, combined with the experimentally-proven fact that HOMs are more stable than the fundamental mode of suitably designed large mode area fibers [7], enables the development of fibers that can yield wavelength conversions at dramatically higher power levels. The index profile and modes used in this analysis, dispersion curves, and the effective area for each of the modes are shown in Fig. 1.

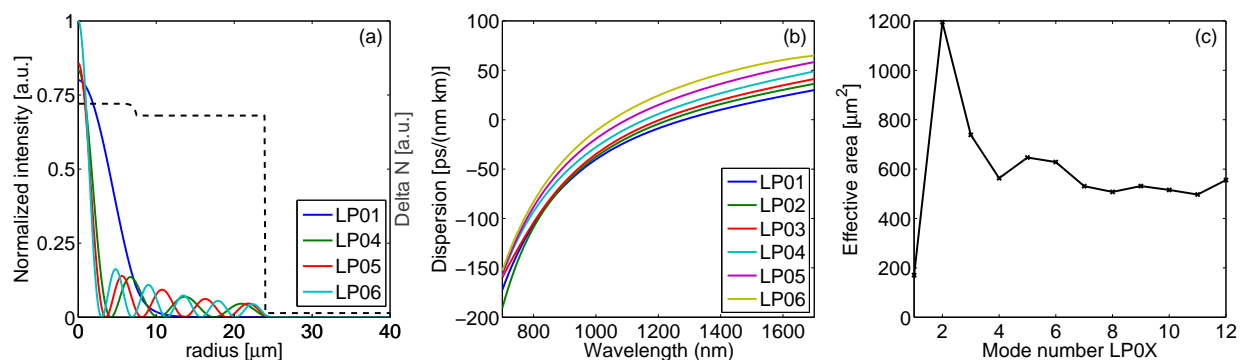


Fig. 1. (a) Intensity plots for the different modes and the power-law double clad index profile (dashed line). (b) Dispersion for the  $\text{LP}_{0X}$ -modes, note that the ZDW decreases with increasing mode order. (c) Effective areas as a function of  $\text{LP}_{0X}$ -modes at 1000 nm.

The gain from the four-wave mixing process in a fiber is highest when the phase mismatch,  $\Delta\beta$  between the pump, idler and signal lies within the gain boundaries defined by  $0 > \Delta\beta > -2n_2/c(P_{p1}\omega_{p1}/A_{\text{eff},p1} + P_{p2}\omega_{p2}/A_{\text{eff},p2})$  [1], this is depicted by dashed lines in Fig. 2a) and Fig. 2b) for the cases when the energy of the generated pulses exceed 1 mJ. For the fiber design of Fig. 1a), the  $\text{LP}_{06}$  mode has a ZDW at 1052 nm, and pumping this fiber in the  $\text{LP}_{06}$  mode at wavelengths around this ZDW value yields gain spectra reminiscent of modulation instability regimes [1] or sharp,

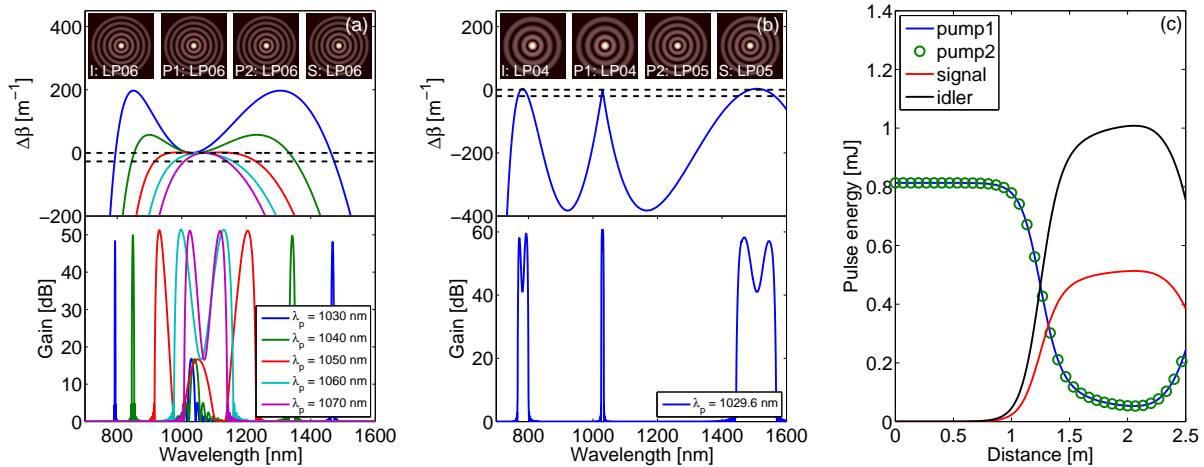


Fig. 2. Phase matching curves for the degenerate pump condition. Dashed lines indicate the regions of high gain. Gain spectra calculated after 1 m of propagation. Insets show the intensity profiles for modes used for the idler (I), pumps (P1 / P2), or signal (S), respectively. (a) Monomodal case: all interacting waves are in the LP<sub>06</sub> mode, with ZDW = 1052 nm. (b) Intermodal case: Idler and pump1 are in the LP<sub>04</sub> mode, while pump2 and signal are in the LP<sub>05</sub> mode. (c) Power evolution of the pump, signal and idler for the intermodal case, illustrating that: (i) the pump undergoes almost 100% conversion; and (ii) idler achieves 1 mJ pulse energies

narrow FWM regimes [6] in single mode fibers, as seen in Fig. 2a). The key distinction is that this happens when the mode area is 600  $\mu\text{m}^2$ , yielding very high-power amplification of the signal and idler.

A much more interesting result is achieved, and indeed, the power of multimode FWM is illustrated, when the idler and pump1 are in the LP<sub>04</sub> mode, and pump2 and the signal are in the LP<sub>05</sub> mode, referred to, henceforth, as the 4455 arrangement. Fig. 2b) shows that, when the pumps are degenerate in wavelength (but not in modal order), a broad gain bandwidth is obtained even while preserving large wavelength separation - a feature that, to the best of our knowledge, has not been observed in the multitude of specially designed dispersion tailored fibers for FWM applications. The zero gradient for the PMC in the gain region immediately suggests stability against ZDW fluctuations in the fiber, which, in turn, indicates that this regime would be robust to fiber diameter fluctuations - usually the bane of efficient wavelength conversion via FWM. The 4455 arrangement preserves the central feature of HOMs - its large area - enabling high-power wavelength conversion operations. The power evolution plot in Fig. 2c), shows that two 45 ns pump pulses with peak powers of 19 kW in the LP<sub>04</sub> and LP<sub>05</sub> modes, respectively, yield a 1 mJ pulse at 776.8 nm. The large mode areas of the participating modes ensure that we operate under the dielectric breakdown threshold while also avoiding efficiency degradation due to SPM or XPM. And, the appropriate choice of modes ensures complete phase matching - photon-to-photon conversion efficiencies approaching 100% are obtained for this case.

In summary, we propose, and theoretically analyse a new regime of operation in fibers, which enables ultra-high-energy wavelength conversion across broad wavelength bands and over large bandwidths. Intermodal four-wave mixing provides this interesting regime of operation because of the fact that, in analogy to PCFs, the zero-dispersion-wavelengths of HOMs can be moved by design (choice of mode order), but unlike PCFs, this does not entail sacrificing mode area (and thus pulse energies at which efficient wavelength conversion is possible). Simulations indicate over 100-nm bandwidths, wavelength conversion ranges exceeding an octave, and pulse energies exceeding a mJ, by using appropriate combinations of modes for pumps, signals and idlers. We expect that this new regime of operation could play a critical role in realising high-power lasers at wavelengths where efficient gain dopants are unavailable.

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